TARDEC Ground Vehicle Robotics:

Vehicle Dynamic Characterization and Research

by

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Introduction

Vehicle dynamics, especially for military applications, has become a highly researched and published topic. Starting from the creation of the first automobiles, the analysis techniques for the dynamics of these vehicles has been developed constantly. Once computers became commonplace, the modelling capabilities of researchers increased dramatically. The goal of this paper is to introduce and define some military and civilian vehicle types that are common, detail some of the methods used to numerically evaluate vehicle mobility, and provide an overview for some of the more common methods and hardware used to experimentally determine vehicle characteristics.

Physical Vehicle Design Properties

The physical components of a vehicle naturally have a large effect on its performance. Body and chassis type have the largest effect on overall vehicle mass, while things like suspension design and drive train construction can greatly affect the lateral and longitudinal capabilities of a vehicle. This section will list vehicle classifications, vehicle design choices and how they affect characteristics important to vehicle dynamics, and original equipment manufacturers (OEMs) and contractors that are involved in the military vehicle market.

All-Terrain Vehicle Classification

The following is a list and description of the different classifications of military armed vehicles described in the Treaty on Conventional Armed Forces in Europe [12]:

Tanks: Tracked and armored vehicles weighing at least 16.5 metric tons unladen*, with a main gun larger than 75mm caliber that can rotate 360 degrees about the body of the vehicle. Wheeled vehicles that meet the above criteria will also be deemed as tanks.

Armored Combat Vehicles: Self-propelled vehicle with armor protection and cross-country capability. These vehicles include the following:

Armored Personnel Carrier: An armored combat vehicle designed to transport combat infantry and is armed with either a mounted (crew serviced) weapon or hand held weapon of less than 20mm caliber.

Armored Infantry Fighting Vehicle: An armored combat vehicle designed and equipped to transport a combat infantry squad, and which provides the capability for the troops to deliver fire from inside the vehicle protected by armor. This vehicle must be armed with either a mounted (crew serviced) weapon or hand held weapon of at least 20mm caliber and sometimes an antitank missile launcher. This vehicle serves as the principle weapon system for armored, mechanized, and motorized infantry formations.

Heavy Armament Combat Vehicle: An armored combat vehicle with a gun of at least 75mm caliber, weighing at least 6 metric tons unladen*, and which does not fall into any of the classifications for armored personnel carrier, armored infantry fighting vehicle, or battle tank.

***Unladen Weight:** Weight of vehicle excluding ammunition, fuel, oil, removable armor, spare parts, tools, accessories, snorkeling equipment, crew, and personal equipment.

UGV Classification

There are two main situations that unmanned vehicles are considered a better alternative to manned operations. First, and considered most important by many, is any dangerous situation that could otherwise injure or kill someone. A great example of this is a bomb squad robot. More often than not, these robots are used to assess a bomb site to decide how to deal with the charge. Instead of having a soldier or civilian officer inspect the bomb by hand, driving the robot up remotely keeps these people much further from the blast zone. The second situation where unmanned ground vehicles are being developed is in jobs that can induce human error based on fatigue or stress. An example of this is autonomous long haul convoy movement, where vehicles travel in packs for hundreds of miles at a time by following a leader vehicle with technologies like machine vision and GPS waypoint setting and following. The following is a list and description of the three main types of unmanned ground vehicles:

Remote Controlled Operation: An unmanned vehicle that is operated by a human. This term specifically describes a system which must remain within the line-of-sight of the operator, because there is no camera feedback. This can be limiting for stealth and long distance operations, but can be a cheaper solution if the situation does not require stealth, as in sacrificial mine clearing or something of that nature.

Teleoperation: An unmanned vehicle that is operated by a human. This term specifically describes a system which does not necessarily need to remain within the line-of-sight of the operator to function. To achieve this, a camera is mounted on the vehicle and the feed is transmitted back to the operator to be monitored. This can be used for many applications, namely long distance or building searching operations. This is the preferred method of human operated robotics because the operators are able to be much farther away from the situation the robot is being sent in to.

Autonomous Operation: An unmanned vehicle that operates based on its own sensors and control laws without the real time input of a human operator. These vehicle systems are becoming more prevalent in recent years. The system uses its sensors to develop a certain awareness of the environment around it. With this awareness, control algorithms are used to have the vehicle make decisions about what actions to take. These vehicles can be used as scouts, follow waypoints to make resupply an unmanned operation, and develop new paths through terrain that are more efficient and safer for manned convoys to travel.

OEMs in Military Vehicle Engineering

Many government contracts involving ground vehicles are outsourced, in part or in full, to private manufacturers and contractors. This helps the military get the most out of their investment because they can choose who gets signed to work on a project based on bidding price, along with previous work done by the companies. The following is a list of a few well known OEMs and contractors, along with some of the military vehicle projects they have worked on, most of which can be found within 10 to 15 miles from the TARDEC facility in Detroit:

Oshkosh Defense:

Light Tactical: JLTV, HMMWV, L-ATV, S-ATV

Medium Tactical: Family of Medium Tactical Vehicles (FMTV)

Heavy Tactical: Heavy Expanded Mobility Tactical Truck (HEMTT), Heavy Equipment Transporter (HET)

Mine-Resistant Ambush Protected (MRAP): M-ATV

Vehicle Systems: CORE 1080 (Crew protection, perception, and survivability system), TAK-4 (Independent Suspension System, applicable to many light and medium weight tactical vehicles, including the complete MRAP series), PROPULSE (Hybrid Diesel-Electric System with Export Power), Command Zone (integrated vehicle control and diagnostic system), and TerraMax (Unmanned ground vehicle technology)

Lockheed Martin Corporation

They work on many different types of vehicles, but have only one ground vehicle project in the works. The JLTV is the one ground vehicle project that Lockheed Martin is working on, and they are working in a partnership with BAE Systems.

BAE Systems

Amphibious Combat Vehicles

Armored Multi-Purpose Vehicle (AMPV): Tank without a turret

CV90: Tank

BR90: Mobile bridging system.

Bradley Fighting Vehicle: Tank

RG33 Mine-Resistant, Ambush Protected Vehicle (MRAP)

General Dynamics Corporation

Abrams Tank: Main Battle Tank

Light Armored Vehicles (LAV): Stryker and LAV family of vehicles

Mine-Resistant, Ambush Protected Vehicle (MRAP) Family

AM General, LLC

Blast Resistant Vehicle-Off Road (BRV-O): Their JLTV offering

High Mobility Multi-purpose Wheeled Vehicle (HMMWV/Humvee): Classical canvas version and up-armored version.

Modernized Light Tactical Vehicle (MLTV)

M-1165 2.0 Deployable Reconnaissance Ground Network-Vehicle (DRGN-V)

General Vehicle Designs and Specifications

This section lists different types of components and system types for a few different subassemblies that would be common on ground vehicles.

Powertrain Systems: Gas Powered, Diesel, Turbo Diesel, Gas Turbine, Hybrid: Gas-Electric, Diesel-Electric, Series, Parallel.

Power Distribution: RWD, FWD, AWD, open diff, LSD, Torsen diff, differential braking (traction control), drive by wire electric, Electric traction control.

Suspension Styles: Suspension is what keeps the vehicle off the ground and mechanically isolated from the terrain irregularities. The suspension usually consists of a spring component and a damping component attached to points on both the main chassis of the vehicle and a mounting point on the suspension linkage. Different types of suspension have niches in different situations. Sometimes a dependent suspension is much more suitable, while other times an independent suspension is much more suitable for the vehicle’s needs.

Dependent: I-Beam, Panhard Rod, Leaf Spring, satchel link, watt's linkage, WOB Link, Mumford Linkage.

Independent: Swing Axle, Sliding Pillar, MacPherson Strut, Double Wishbone, Multi-link, Semi trailing arm, Swing Arm, Leaf Springs

Tire Choices: Most vehicles are going to have some type of all-terrain tires that will be able to traverse most anything effectively. The size and strength of these tires depends more on the weight and performance capabilities of the vehicle they are on. Some type of run-flat tires should be mentioned, but they are usually much heavier than classic pneumatic tires. Also, bead-locking rims could be quite beneficial for certain applications, especially those where lower tire pressure would be necessary to get through a certain path, like in extremely rocky or muddy terrain.

Definitions and Numerical Simulations of Vehicle Characteristics

Being able to objectively assess the mobility of a vehicle is critical in its design and development process. Without being able to characterize the performance of a vehicle, critical metrics that define a vehicle's motion would be hard to know accurately, and therefore meaningful design changes would be hard to verify without physically constructing prototypes. In this section, general definitions of mobility, along with mathematical expressions that provide a basis for vehicle dynamic simulation, will be discussed. Also, demonstrations of how vehicle parameters affect the performance of a vehicle are presented. The relationship between the vehicle and the terrain it is traversing is mentioned, but not deeply discussed.

Vehicle Mobility

Vehicle mobility in military applications is beginning to be better defined by standards like the NATO Reference Mobility Model (NRMM), which is the standard in the Army Battle Command, Simulation, and Experimentation Directorate for single vehicle ground movement [13]. These standards continue to be developed and defined by the Army Corps of Engineers, whose development of computer models for vehicle mobility is generalized to accommodate multiple vehicle platforms, unlike previous models that needed to be redesigned for different parameters [13].

Essentially, mobility is the ability of a vehicle to maneuver and navigate over a specified terrain as it is influenced and changed by weather and other environmental conditions [3]. There are multiple ways to define the ever- changing vehicle-terrain dynamic model, such as the Nepean Wheeled/Tracked Vehicle Performance Model. Demand for engineers and designers in both the private and the military sector is becoming more and more evident, as companies and government agencies realize the importance of computer simulation in the prototyping process [14]. Studies detailing the effects of torque distribution on the tractive ability of vehicles have also been conducted in the hopes of finding a way to actively tune traction control software to the current terrain [11].

Along with the analysis of single vehicles, there is growing interest in the study of the collective dynamics of a group of vehicles. This analysis can involve the effect of new tread marks in terrain on a follower vehicle's dynamics, and can also detail how communication between the vehicles within a convoy can allow follower vehicles to alter power distribution to make the most out of available traction [6], [10].

The easier part of the analysis of a vehicle's mobility is finding the dynamic characteristics of a vehicle on an assumed flat surface. The hard part is accounting for terrain, especially natural and/or dynamic terrain that can change as it is being driven on. There should be a direct correlation between terrain "severity" and the ability of a vehicle to maneuver through it. Some models solve this issue by concocting a terrain factor that will essentially be used to modify the ideal model of the vehicle [7]. This can only serve as an estimation, and because of this, sensor data and dynamic modelling with sensor input is invaluable to aid in the understanding of how the characteristic handling of a vehicle change on different terrain.

Terrain characteristics can be defined with testing like cone penetrometers, measuring the force needed to push a metal cone into the ground a certain distance [14]. Different types of soil can also be defined by factors like soil density and yield of oat as it is compacted by multiple vehicle passes [6]

Analytical Resources

Traction and tire slippage are two main criteria for mobility, because all of the ground forces are transferred to the vehicle from the ground via the tires. Therefore, traction is usually the factor, more than any other factors, which limits the vehicle's mobility. Some other criteria are longitudinal top speed, acceleration, and braking capabilities.

Another component of vehicle mobility that is very important is the ability to create yaw moment and therefore yaw acceleration, which translates to a lateral acceleration of the vehicle. This factor can be characterized by something called an understeer gradient, which is the difference of the theoretical ratios of the front and rear weights divided by the tire slip angle being experienced in either the front or the back. It can also be described as the ratio of steer angle over lateral acceleration. This gradient essentially describes how a vehicle would react as it travelled around a certain radius turn with a continuous acceleration. A positive understeer gradient means that the vehicle is understeer, a negative understeer gradient means that the vehicle is oversteer, and an understeer gradient of zero means the vehicle is neutral steer. Understeer means that as the vehicle velocity is increased, the steer angle necessary to stay on the radius of the turn will increase. Oversteer means that as the vehicle velocity is increased, the steer angle necessary to stay on the radius of the turn will decrease. Neutral steer means that as the vehicle velocity is increased, the steer angle necessary to stay on the radius of the turn will be constant. [5]

An important factor in low speed vehicle cornering has to do with turning radius and steer angles. There is a relation called Ackermann steering, which is simply a relation between the inside and outside tire angles in a turn. This also has to do with wheel base length. The modelling of the physical body movement of the vehicle is not too difficult. The hard part is defining and characterizing the forces the tires can give out. This characterization can be done with something called the Pacejka method, or The Magic Formula. This formula is literally derived from Hans looking at experimental data and trying to make a mathematical curve fit the experimental data as closely as possible. Many vehicle dynamics simulations use this curve to define the tire forces. Sometimes though, in simpler models, the tire curve can be defined as a line that ends at the peak force of the tire. This is obviously inaccurate, but is sufficient for certain calculations. [5] Some other tire models will be described later.

Equations: (** - From Gillespie [5])

Low Speed Maneuvering **: Unlike steady state maneuvers at speed, tires don't need to generate lateral forces in low speed or "parking lot" maneuvers. Because of this, they roll with no slip angles. This means that the steering angles of the front wheels must be calibrated perfectly to allow a no slip condition while turning. The steer angles can be expressed as

$$\delta_o = \frac{L}{R + \frac{t_f}{2}}$$

and

$$\delta_i = \frac{L}{R - \frac{t_f}{2}}$$

With the average front wheel angle, known as the Ackerman Angle, is given by

$$\delta = \frac{L}{R}$$

assuming small angles.

Tire Models [2]: Tire models take in slip angles and output a lateral force generated by that slip angle. The simplest model applies a strictly linear relationship between slip angle and lateral force. There are two other models that are quite common: The Pacejka Model, and the Duggoff Model.

Pacejka Model: The Pacejka model was developed essentially by taking experimental data and developing an equation that fit the curve of the data as closely as possible. The problem with this is that the coefficients of the equations change for each tire type, and the only way to know is to either run experiments to find the coefficients or look up tables and try to find the tire you are using on a surface similar to what you want to analyze. There are many, many different things that can affect the specific values for these curves, but they are nonetheless good estimates. The Pacejka model is defined as follows:

$$D = a_1 F_z^3 + a_2 F_z^2 + a_3 F_z$$

$$BCD = a_4 \sin(a_5 \tan^{-1}(a_6 F_z))$$

$$E = a_7 F_z^2 + a_8 F_z + a_9$$

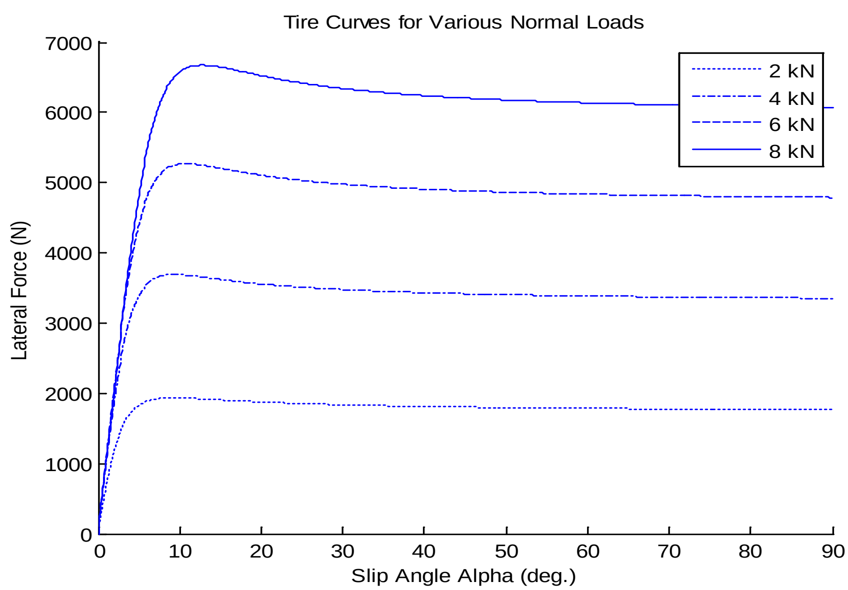
$$B = \frac{BCD}{CD}$$

$$\varphi_{Pac} = (1 - E)\alpha + \frac{E}{B}\tan^{-1}(B\alpha)$$

$$F_y = D\,\sin(C\,\tan^{-1}(B\,\varphi_{Pac}))$$

where $a_1 - a_9$ and C are variables found from experimental data, A, B, D,E, and φ_{Pac} are calculated values with no physical meaning, F_z is the normal force on the tire, and α is the tire slip angle.

The shape of a standard Pacejka curve at different normal loads can be seen below.



Duggoff Model: The Duggoff tire model is probably the most practical tire model available. It is so useful because it can be defined based only on physical characteristics, instead of the crazy polynomial fit coefficients that the Pacejka model uses. It is also more accurate than a linear model because it flattens out after a certain slip angle, similar to the Pacejka curve. The Duggoff Model can be expressed as

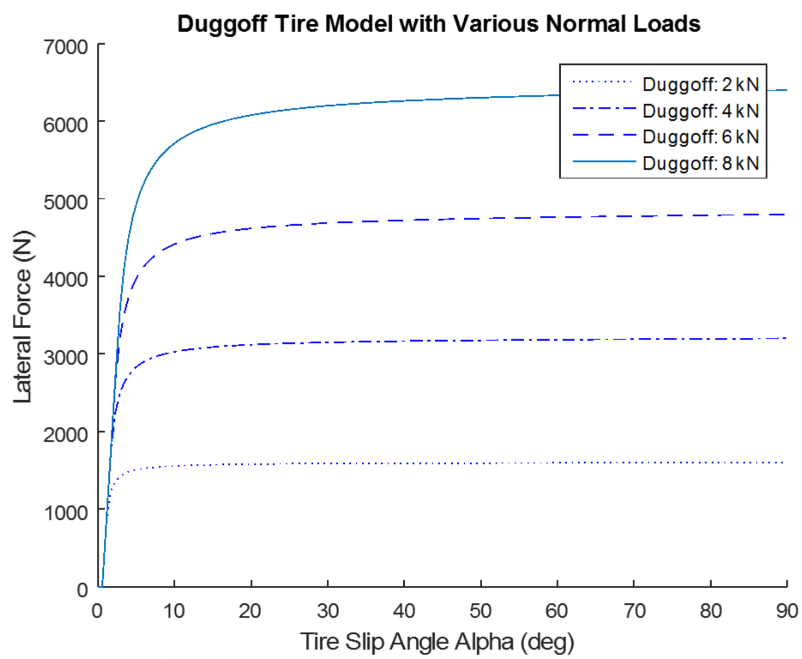
$$\lambda = \frac{\mu_{pk}F_z}{2C_\alpha|\tan(\alpha)|}$$

$$f_{(\lambda)} = \begin{cases} (2-\lambda)\lambda & if \quad \lambda < 1 \\ 1 & if \quad \lambda > 1 \end{cases}$$

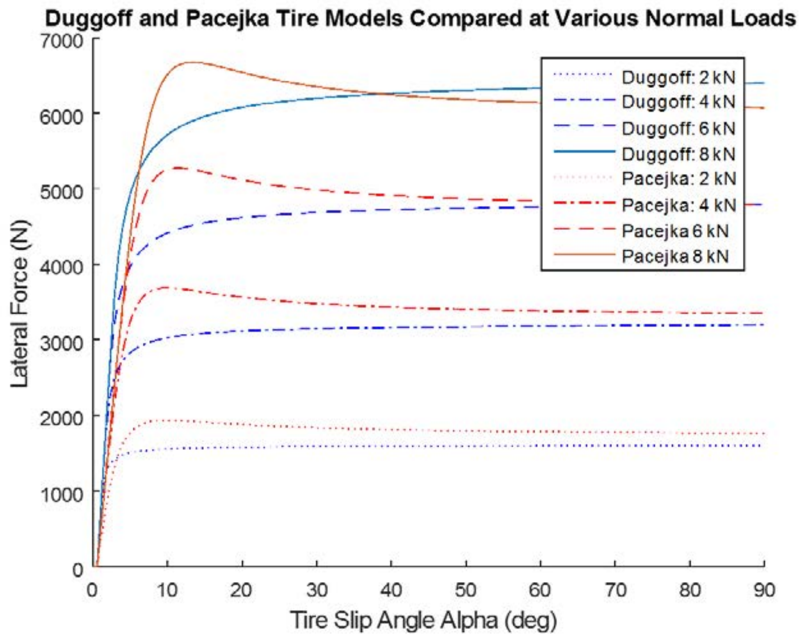
$$F_y = C_\alpha \tan(\alpha)\, f_{(\lambda)}$$

where μ_{pk} is the peak coefficient of friction between the tire and the ground.

The Duggoff curve can be seen below at various different normal loads.



Below is a comparison between the Duggoff and Pacejka curves. They are relatively close.



Steady-State Cornering **: This segment is performed under the bicycle model assumptions that the difference between the inside and outside slip angles in the front and rear, along with the steer angles, is small enough to be neglected. This means there is one set of angles per axle. Things like camber thrust, and the kinematic effects of the suspension on camber and steer angles, are neglected in these equations.

Lateral Axle Force **:

$$F_{yr} = M\frac{b}{L}\left(\frac{V^2}{R}\right)$$

$$F_{yf} = F_{yr}\frac{c}{b}$$

where F_{yf} is the lateral force on the front axle, F_{yr} is the lateral force on the rear axle, M is the vehicle mass, b is the distance from the cg to the front axle, c is the distance from the cg to the rear axle, L is the total wheelbase length, V is the longitudinal velocity, and R is the radius of the turn.

Steer Angle **:

$$\alpha_f = W_f \frac{V^2}{C_{\alpha f} g R}$$

$$\alpha_r = W_r \frac{V^2}{C_{\alpha r} g R}$$

$$\delta = 57.3 \frac{L}{R} + \alpha_f - \alpha_r \Rightarrow 57.3 \frac{L}{R} + \left(\frac{W_f}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}} \right) \frac{V^2}{gR}$$

$$K = \frac{W_f}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}}$$

$$a_y = \frac{V^2}{gR}$$

$$\delta = 57.3 \frac{L}{R} + K a_y$$

where α_f and α_r are the front and rear slip angles, W_f and W_r are the weights on the front and rear axle, $C_{\alpha f}$ and $C_{\alpha r}$ are the front and rear tire cornering stiffness per axle, δ is the steer angle in degrees, K is the understeer gradient, and a_y is the lateral acceleration in g's.

Characteristic and Critical Speeds **:

Characteristic speed is defined as the speed at which the required steer angle to hold the turn radius is twice the Ackerman angle for an understeer vehicle. It is given as

$$V_{char} = \sqrt{57.3\, L \frac{g}{K}}$$

Critical speed is defined as the speed at which an oversteer vehicle will become unstable. It is given as

$$V_{crit} = \sqrt{-57.3\, L \frac{g}{K}}$$

These two definitions imply an important difference between understeer and oversteer vehicles that can be defined when the transfer functions of the systems are analyzed. An understeer vehicle can never go unstable, aka eigenvalues in the right half-plane. But, at a certain point the steering inputs have no effect on the dynamics of the vehicle. On the other hand, an oversteer vehicle can definitely become unstable, but the steering inputs always have effect on the vehicle dynamics. This highlights the reason why most consumer automobiles come from the factory in an understeer configuration, so that if something goes wrong in a maneuver, the car will not go crazy and spin out, and the likely overreaction of the driver wouldn't make the situation necessarily worse. Also, it makes sense now why race teams usually set up their vehicle with neutral steer leaning towards oversteer, so that the driver can maintain control as he or she operates the vehicle near its dynamics limits.

Roll Angle and Weight Transfer **:

$$H = h_{cg} - \left(\frac{h_f + h_r}{2}\right)$$

$$rr = k_{\varphi f} + k_{\varphi r} - WH$$

$$\varphi = \frac{WH}{rr} * a_y$$

$$\Delta F_{z,f} = \frac{k_{\varphi f}\varphi + W_f h_f a_y}{t_f}$$

$$\Delta F_{z,r} = \frac{k_{\varphi r}\varphi + W_r h_r a_y}{t_r}$$

$$F_{f,i} = \frac{W_f}{2} - \Delta F_{z,f}$$

$$F_{f,o} = \frac{W_f}{2} + \Delta F_{z,f}$$

$$F_{r,i} = \frac{W_r}{2} - \Delta F_{z,r}$$

$$F_{r,i} = \frac{W_r}{2} + \Delta F_{z,r}$$

where H is the effective roll moment arm from the ground, h_{cg} is the height of the center of gravity from the ground, h_f and h_r are the height of the front and rear suspension roll centers from the ground, $k_{\varphi f}$ and $k_{\varphi r}$ are the front and rear roll stiffness, rr is the roll rate, φ is the roll angle, t_f and t_r are the front and rear track widths, $\Delta F_{z,f}$ and $\Delta F_{z,r}$ are the weight transfer in the front and rear, and $F_{f,i}$, $F_{f,o}$, $F_{r,i}$, and $F_{r,i}$ are the front and rear inner and outer vertical loads on the tires.

Transient Maneuvering Dynamics [15]: This segment is going to skip all of the derivation of this model because it is pretty intense. I will do my best to mention every assumption, but there are a lot to make this happen. The system can be modelled as follows:

$$C_0 = C_{\alpha f} + C_{\alpha r}$$

$$C_1 = aC_{\alpha f} - bC_{\alpha r}$$

$$C_2 = a^2 C_{\alpha f} + b^2 C_{\alpha r}$$

$$\begin{bmatrix} \dot{r} \\ \dot{V}_y \\ r \\ V_y \end{bmatrix} = \begin{bmatrix} \frac{-C_2}{VJ} & \frac{-C_1}{VJ} & 0 & 0 \\ -\frac{C_1 - MV^2}{MV} & -\frac{C_0}{MV} & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & V & 0 \end{bmatrix} \begin{bmatrix} r \\ V_y \\ \theta \\ y \end{bmatrix} + \begin{bmatrix} \frac{aC_{\alpha f}}{J} \\ \frac{C_{\alpha f}}{M} \\ 0 \\ 0 \end{bmatrix} \delta_{(t)}$$

$$Y = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} r \\ V_y \\ \theta \\ y \end{bmatrix}$$

There are a few new variables in this that we haven't seen yet. V is the longitudinal velocity, but is being assumed as essentially the velocity magnitude to simplify the state equations. r is the yaw rate. V_y is the lateral velocity, and J is the yaw moment of inertia of the vehicle. This model assumes small angles, uses the bicycle model, and uses a modified linear tire model. Side slip angle, or the angle between the velocity vector at the cg of the vehicle and the longitudinal axis of the vehicle, can be found with

$$\beta = \tan^{-1}\left(\frac{V_y}{V}\right)$$

and is very important in the development of traction control algorithms.

Extra Tidbits **: There are a few different little equations that either fit in all of the above situations are standalone equations that shed light on different factors of vehicle dynamics.

Wheel Slip: If there is an acceleration, there will always be wheel slip. Some example data is shown in part 3. The equation to compute wheel slip is

$$\%Slip = \frac{V - R_w\omega}{V} * 100\%$$

where ω is the rotational speed of the wheel and R_w is the wheel radius.

Yaw Velocity Gain: This equation is pretty cool because you can use it to find K_{US} while the vehicle is doing any type of maneuver, instead of just doing the skid pad test, if a few vehicle states are known. This can be expressed as

$$\frac{r}{\delta} = \frac{V/L}{1 + \frac{K_{US}V^2}{57.3\,Lg}}$$

this is a little complicated, but if yaw rate, steer angle, and velocity are being measured and the wheelbase length is known, the understeer gradient can be found without too much effort.

Understeer Increment: This is essentially steering system slop. This has a bit to do with suspension design, which isn't something I want to dive into, so I'll keep the explanations brief and google can fill in the blanks. The expression for understeer increment is given as

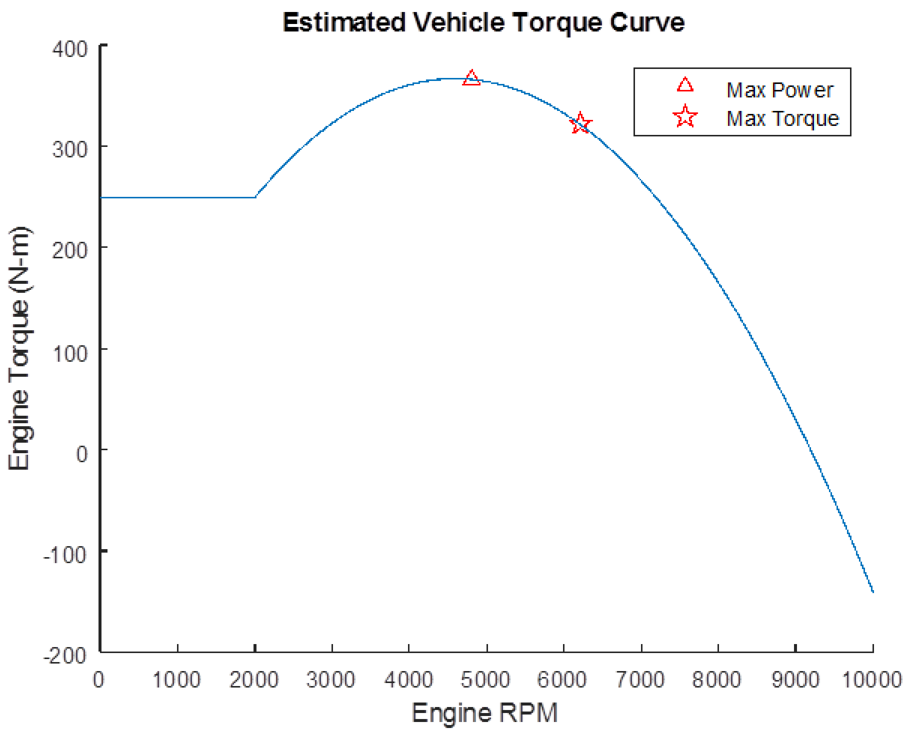
$$K_{US,strg} = \frac{W_f(R_w\nu + p)}{K_{SS}}$$

where $K_{US,strg}$ is the understeer increment due to steering, ν is the Caster angle, or the angle that the wheel rotates around as it is steered when looked at from the side, p is the pneumatic trail, or distance the tire patch is trailing the center of the wheel, and K_{SS} is the spring coefficient between the steering wheel and the wheel on the road.

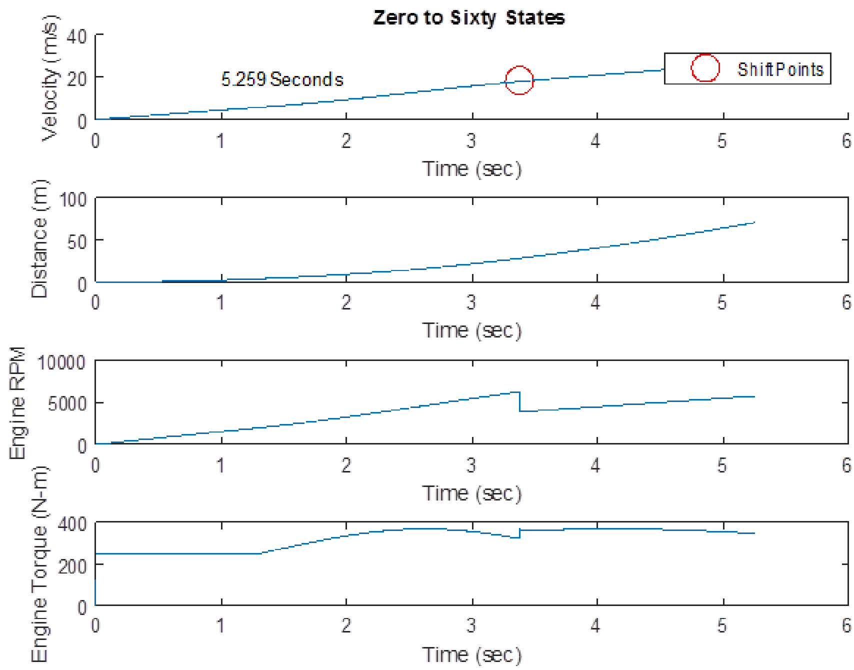
Demonstration of Vehicle Parameter-Dynamic Handling Relationships

The following are a few examples of results from mathematical simulations. There are parameters varied between simulations to demonstrate how the changes affect vehicle performance in simulation:

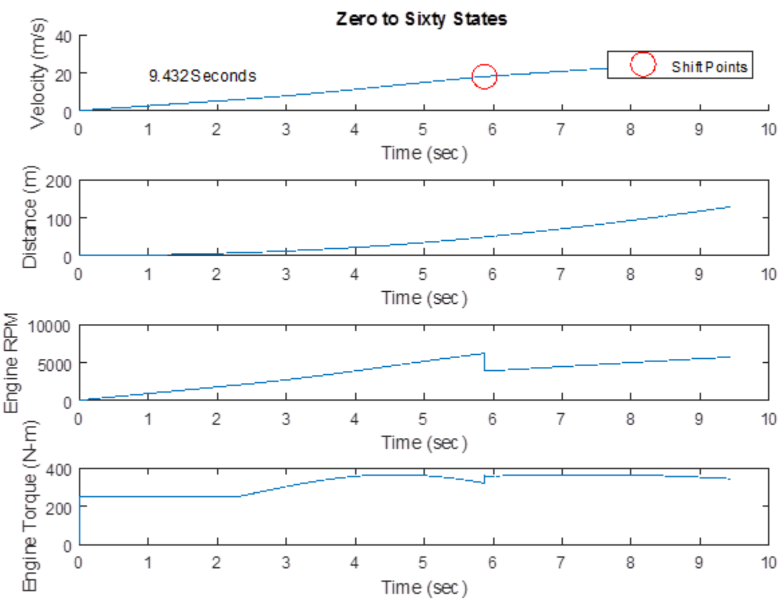
Zero to Sixty Simulation



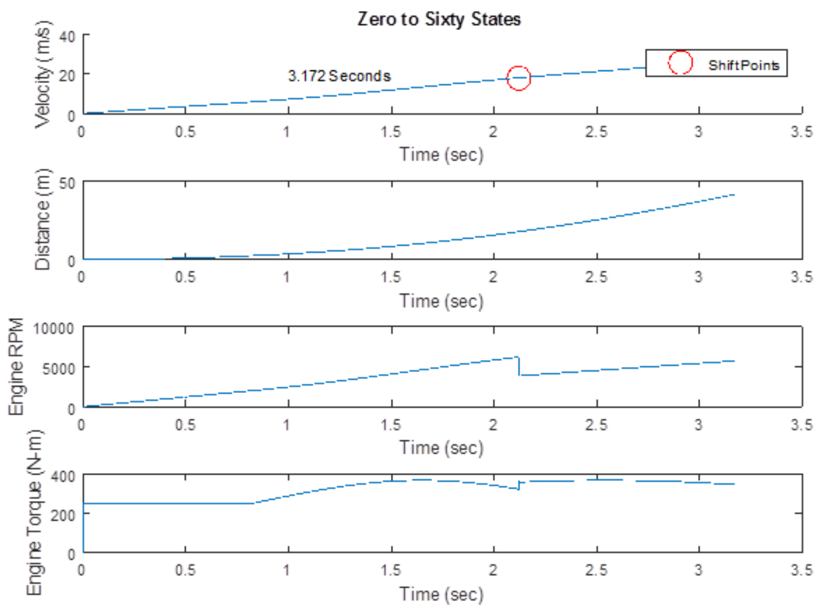
Standard Parameters



Twice the Mass

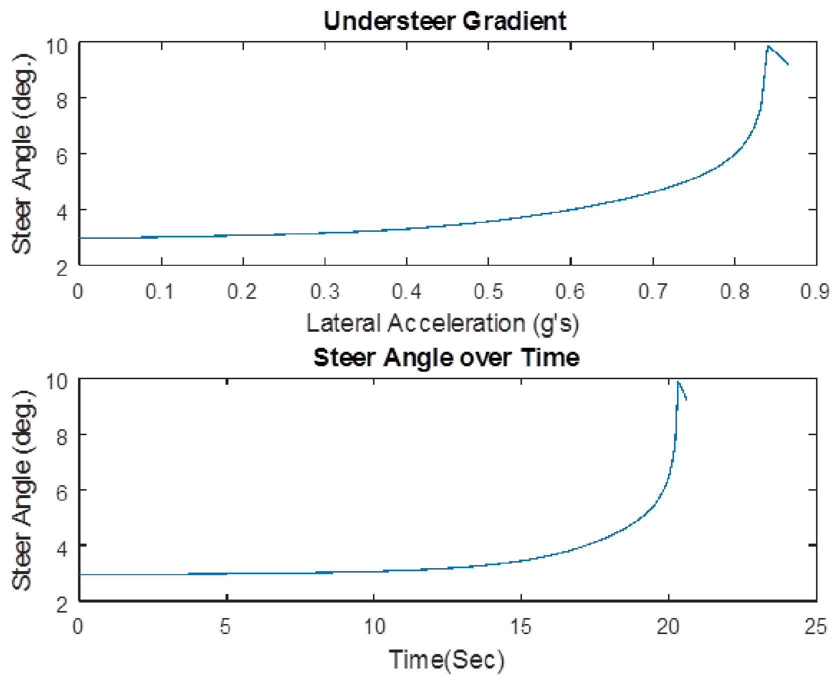


Half the Mass

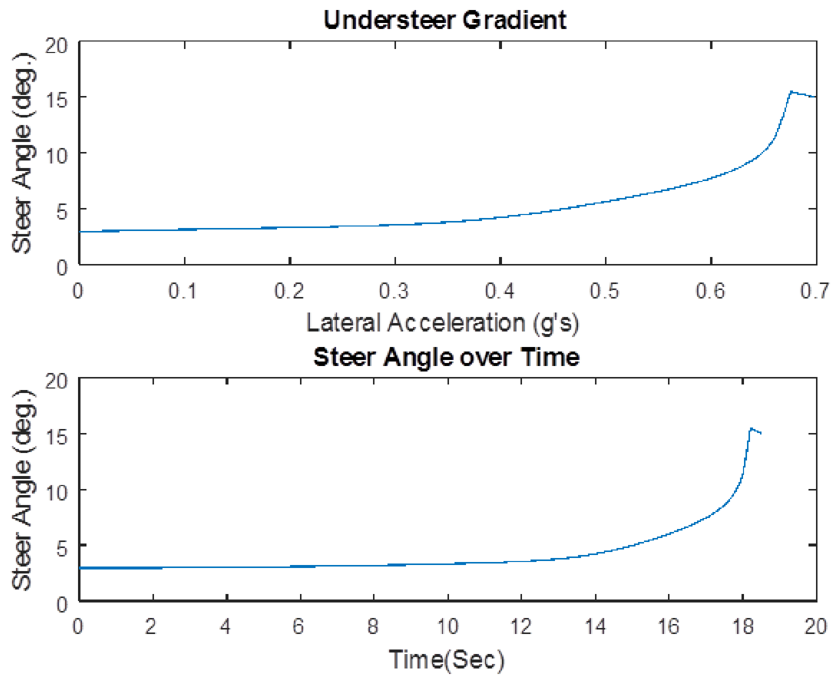


100 meter Skid Pad Simulation

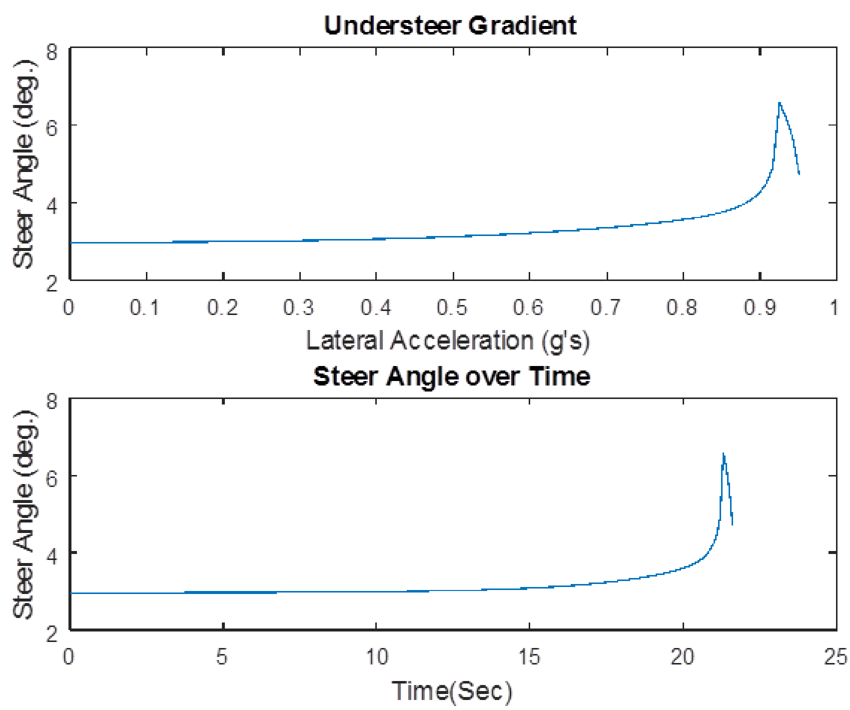
Standard Parameters



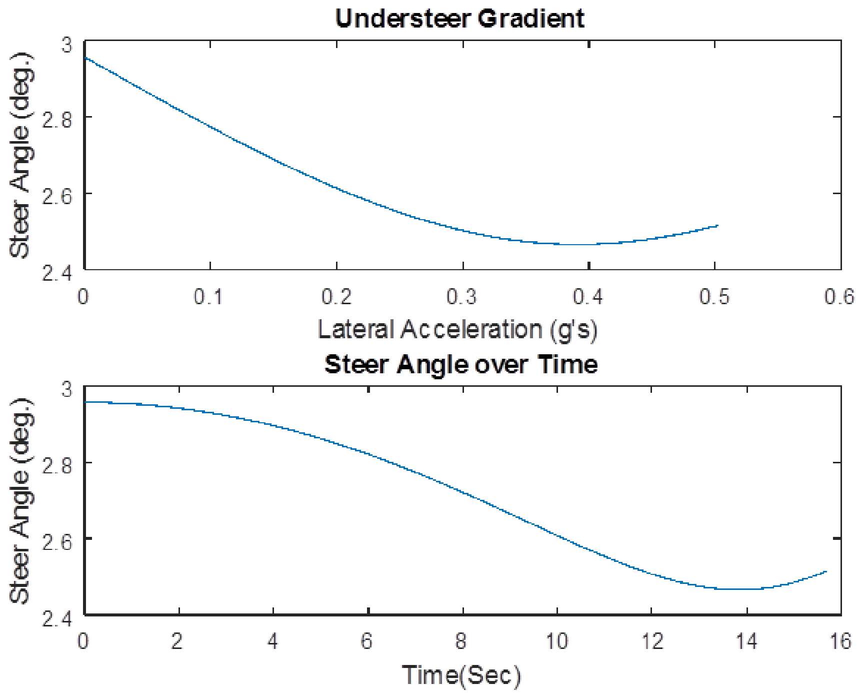
Double the Mass



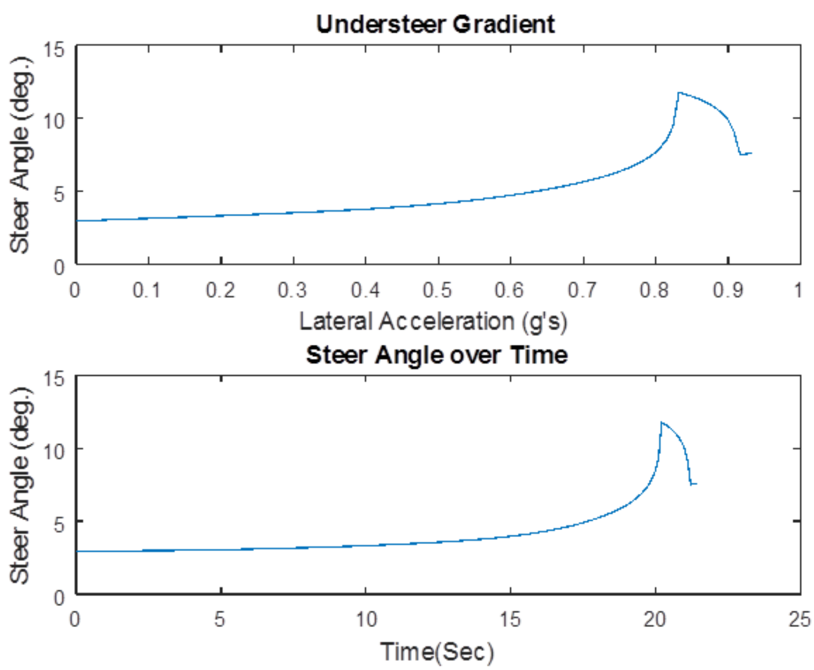
Half the Mass



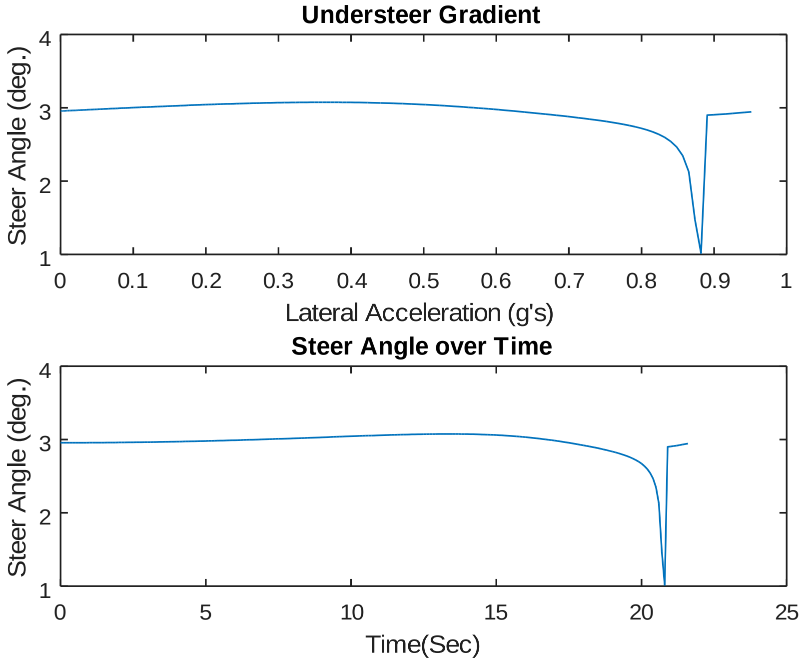
Drastically Rear Heavy



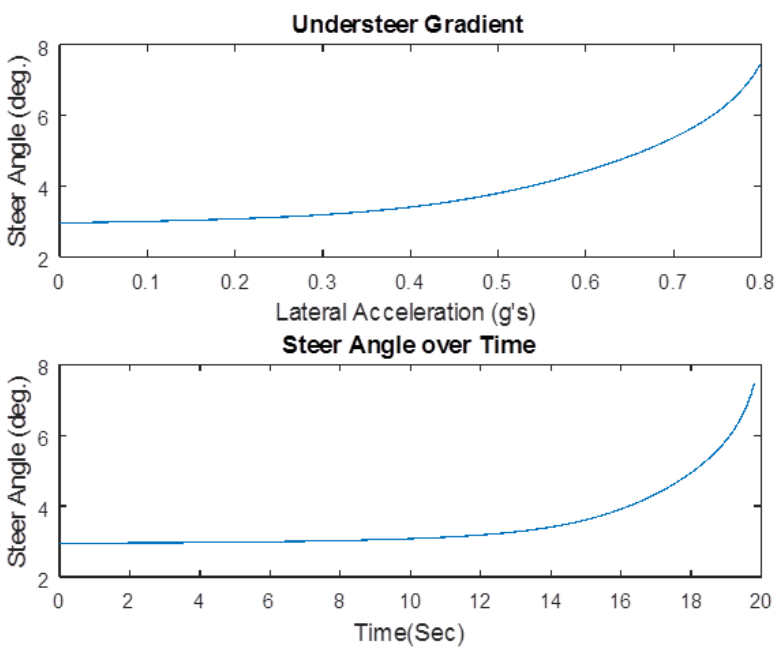
Drastically Front Heavy



Forward Angled Slope between Roll Center Heights

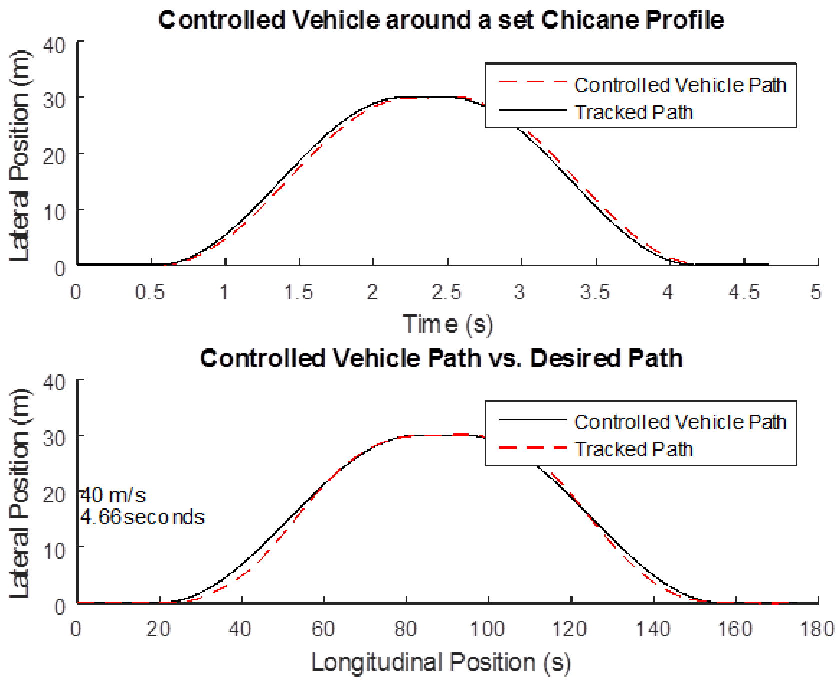


Rearward Facing Slope between Roll Center Heights

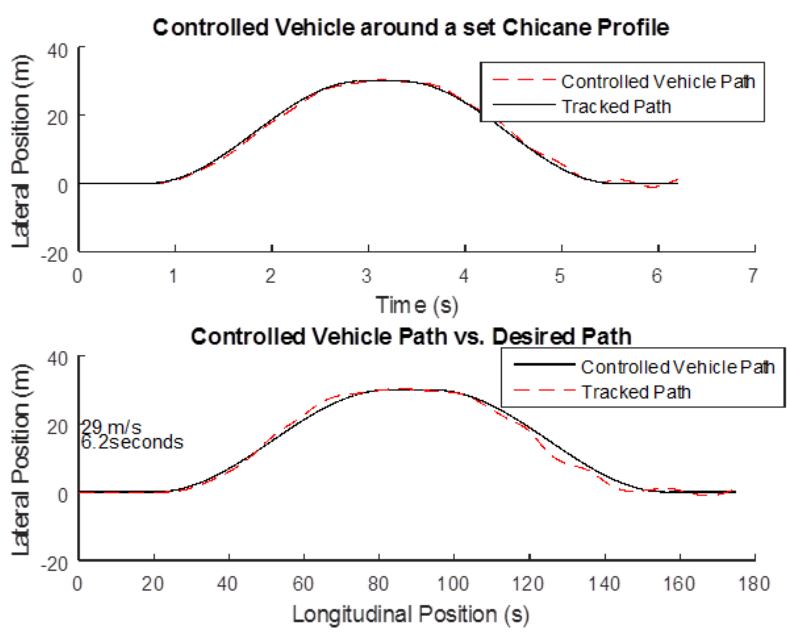


Double Lane Change Maneuver

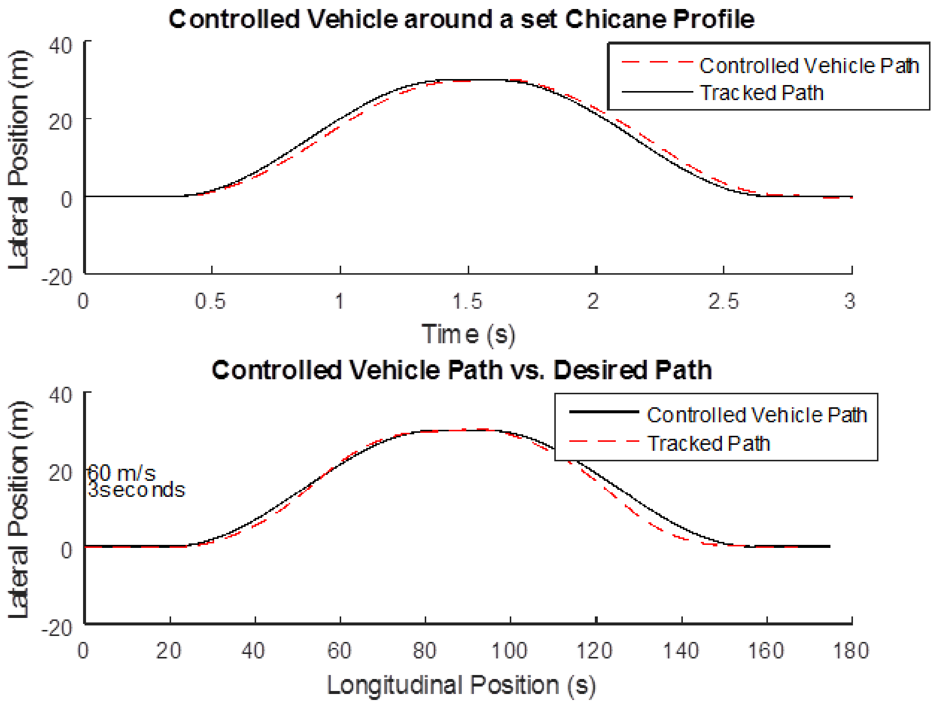
Standard Parameters



Double the Weight



Half the Weight

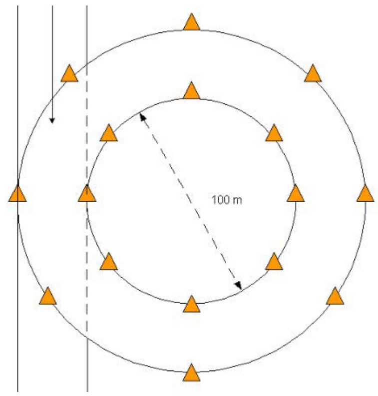


Experimental Methods for Vehicle Characterization

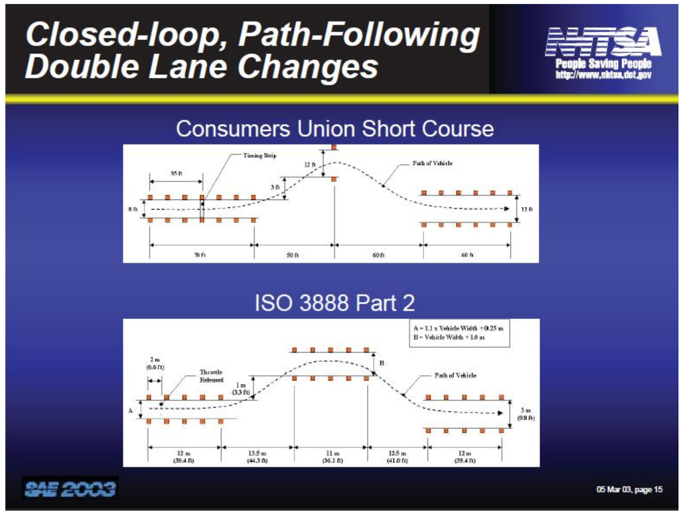
While simulated vehicle testing is extremely useful to aid in the design process, the product eventually has to be made, and the designs need to be validated. That is where experimental real time data logging comes in. While the sensing technologies used today still aren't perfect, they help shine a light on the dynamic vehicle characteristics. In this section, testing techniques, sensors utilized in these tests, and examples of some of the pitfalls of on-line data logging, are described.

Experimental Methods to Estimate Vehicle Mobility

Skid Pad: Starting from rest, a vehicle accelerates slowly around a constant radius turn until the car loses traction and skids out. This test is essential in characterizing the steady state cornering capabilities of the vehicle. When actually done to a real vehicle, it is important that this test is done going both clockwise and counterclockwise around the course.



Double Lane Change: Unlike the skid pad test, most vehicle handling and maneuvers are not steady state; most involve transient weight transfer and conditions. The double lane change is a standard road vehicle test, and can be used both to asses a car's handling abilities and the abilities of an autonomous control system. The test involves the vehicle starting going straight forward, swerving over the distance that two lanes would entail, and swerving back the other direction the same distance. The maneuver is transient because the sudden change in direction induces body roll, and therefore weight transfer which affects the traction of the vehicle [4].



Acceleration and Deceleration: This is pretty straight forward, a car starts at rest and accelerates in a straight line for a certain distance, then slams on the brakes until the car comes back to rest. This is a test of a vehicles longitudinal acceleration capabilities.

Coast Down: This test helps to characterize the air drag, rolling resistance, and/or inertial and viscous losses in the drivetrain, depending on how the vehicle is set up.

Hardware to Estimate Parameters On-Line

Wheel Speed Sensors

Usually Hall Effect Sensors, much less often rotary digital encoders. Encoders are much better at low speed readings, Hall Effect sensors are more reliable for high speed readings. Hall Effect sensors are usually bad for low speed because most of these types of sensors use spokes of some kind, on a structure called a reluctor, to create a signal. If the sensor is between spokes, there is no reading to be made. So between spoke sensor impulses, the speed change is unknown.

IMU and Processors

Accelerometers and gyroscopic sensors are used to measure the transient motion of the vehicle. Gyros are used primarily to find yaw rate. In fact, some purpose made vehicle dynamic IMUs, or inertial measurement units, have only a z-axis gyro, as yaw rate is so important for vehicle dynamic characterization. Accelerometers are useful in all three axis, though they can be misleading if certain precautions aren't taken. Usually the accelerometers are used in a vehicle to find vehicle pitch and roll angles. This helps to characterize vehicle weight transfer. This can be tricky though, because as the vehicle rolls, the lateral acceleration seen in the y-axis gyro is sensing both lateral acceleration and some gravitational acceleration because the vehicle is rolling. It is extremely important that the code used to process the dynamic information from these sensors accounts for body roll in the calculation of lateral acceleration and body pitch in the calculation of longitudinal acceleration.

GPS

GPS sensors aren't accurate enough to give premium vehicle dynamic data yet, but it can be used as a check against the integral of accelerometers to check that the system is calibrated correctly.

Suspension Position Sensors

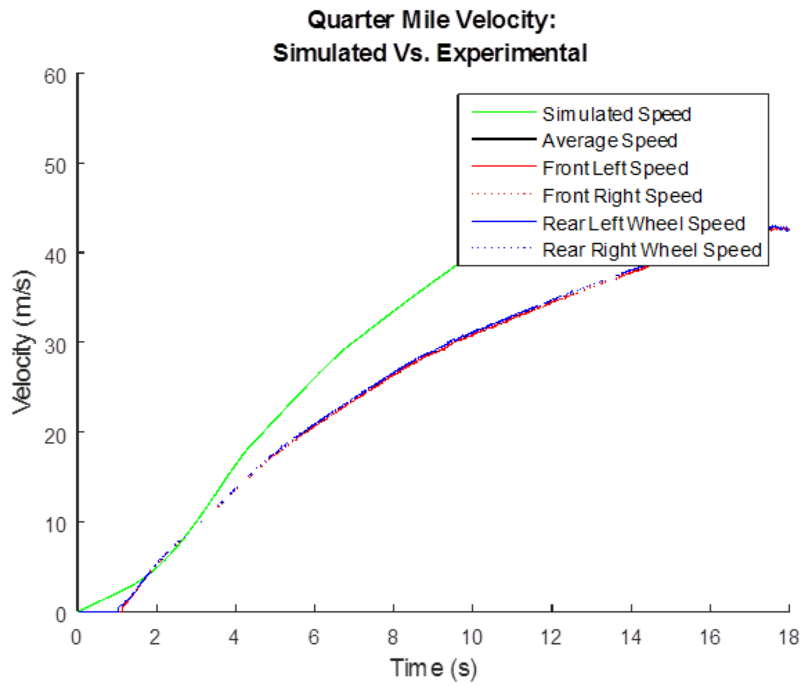
One way to physically verify the position of the suspension to analyze the kinematic properties of the system through different maneuvers. This can be used to both validate the kinematic design software used to design the system, and also can help verify the inferred roll angles that are found with the IMU. This is usually done with linear potentiometers, which have an electrical resistance that changes at a set rate as the length of the device is changed.

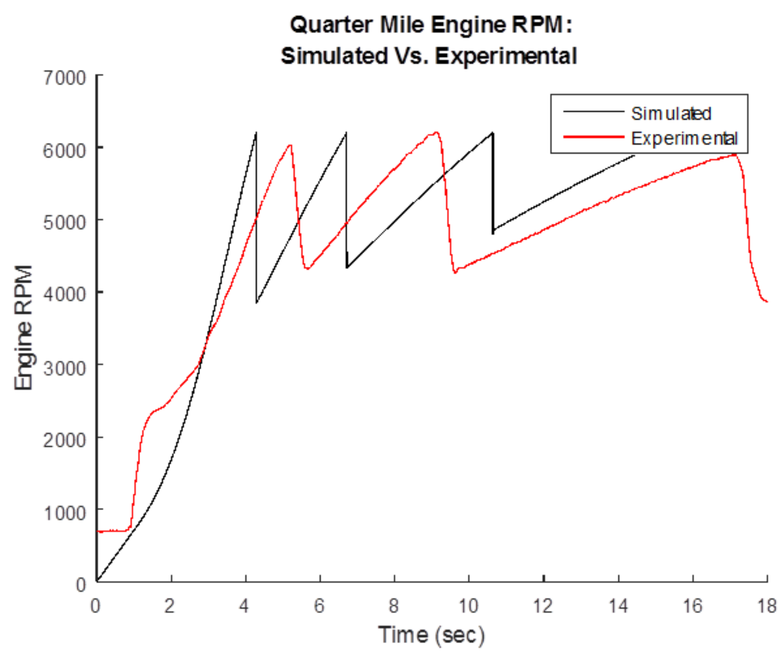
Steering Position Sensors

Helps validate the mathematical relationship between steering input, velocity, and vehicle parameters. These are usually rotary digital encoders, with one part mounted on the column support, and the other end rotating with the steering column. This measurement can be extrapolated through the steering rack ratio to get the input steering angle at the wheels, which is an important measurement in vehicle dynamic analysis.

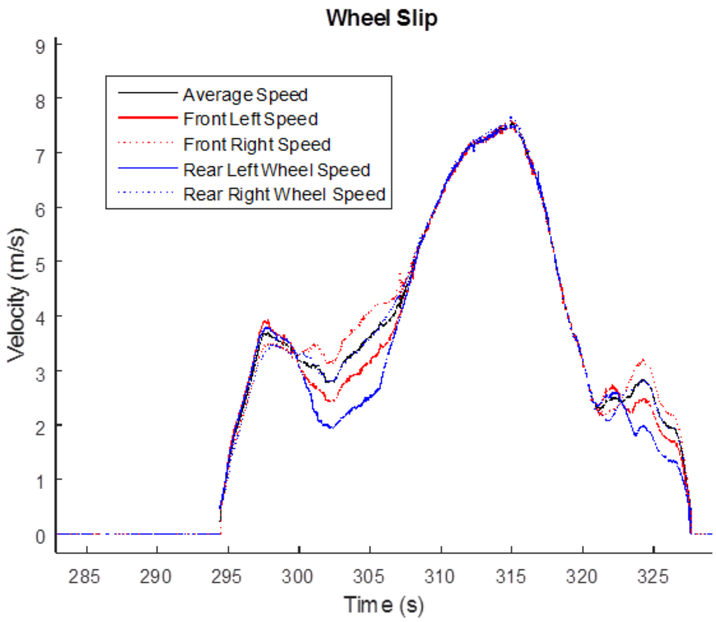
Examples of Experimental Data Analysis

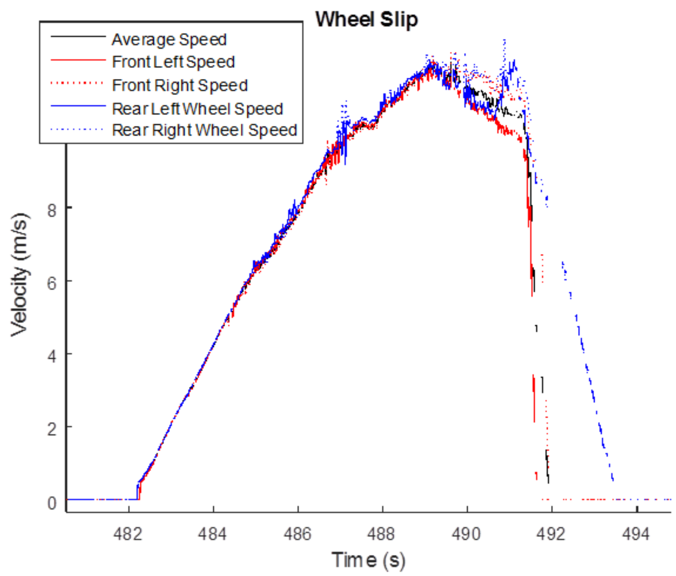
A comparison between velocity and engine RPM measurements from a vehicle's CAN bus as it does a quarter mile race, and the simulation of the same event, can be seen below. There are many different reasons the simulation and experimental data may not line up. Initialization of the simulation may be inaccurate. There may be inherent bias in the sensors. Even though the experimental data has been filtered, there still is likely some small trace of the noise that was present in the raw data.


Quarter Mile Velocity:
Simulated Vs. Experimental
Simulated Speed
Average Speed
Front Left Speed
Front Right Speed
Rear Left Wheel Speed
Rear Right Wheel Speed
Velocity (m/s)
Time (s)
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18

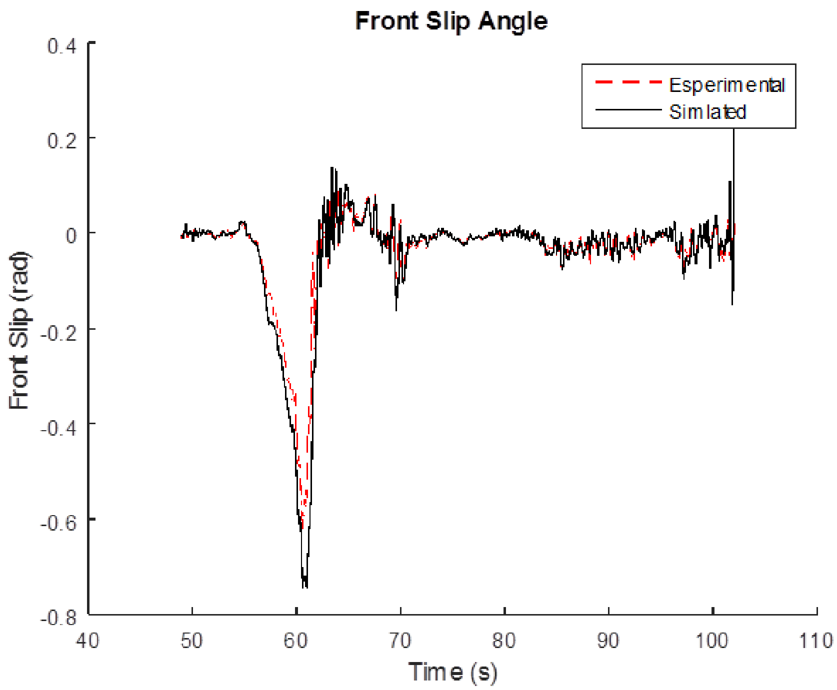

Quarter Mile Engine RPM:
Simulated Vs. Experimental
Simulated
Experimental
Engine RPM
Time (sec)
0
1000
2000
3000
4000
5000
6000
7000
0
2
4
6
8
10
12
14
16
18

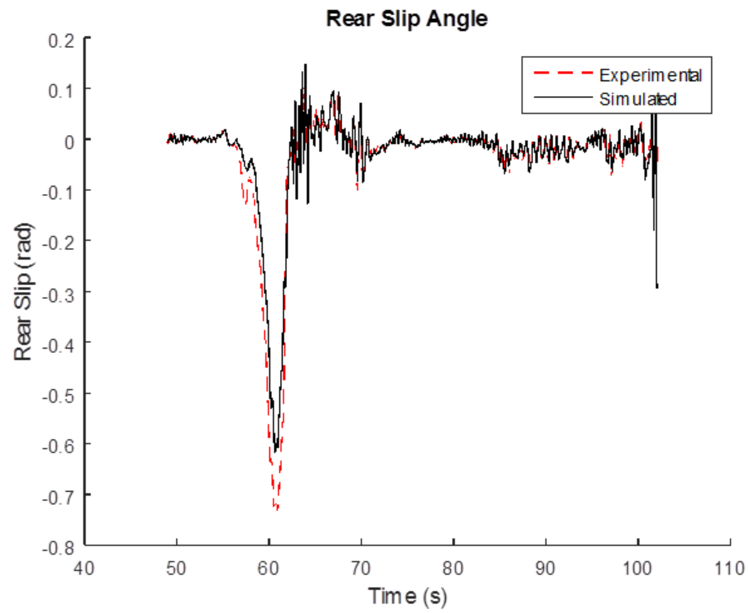
This is another example of some data gathered from a vehicle's CAN bus. This is just the wheel speeds of all four wheels. It is interesting to look at how the wheel speeds vary when the vehicle is taking a turn, as seen in the first plot below. In the second picture, data was collected while slamming on the brakes in loose gravel. It is clear that the ABS is failing for the front tires, but the rear tires are well controlled and do not skid.

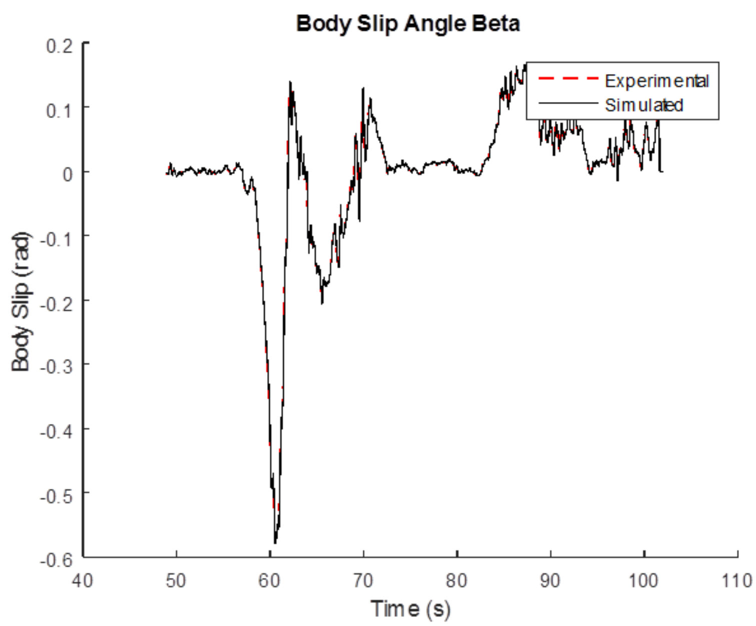


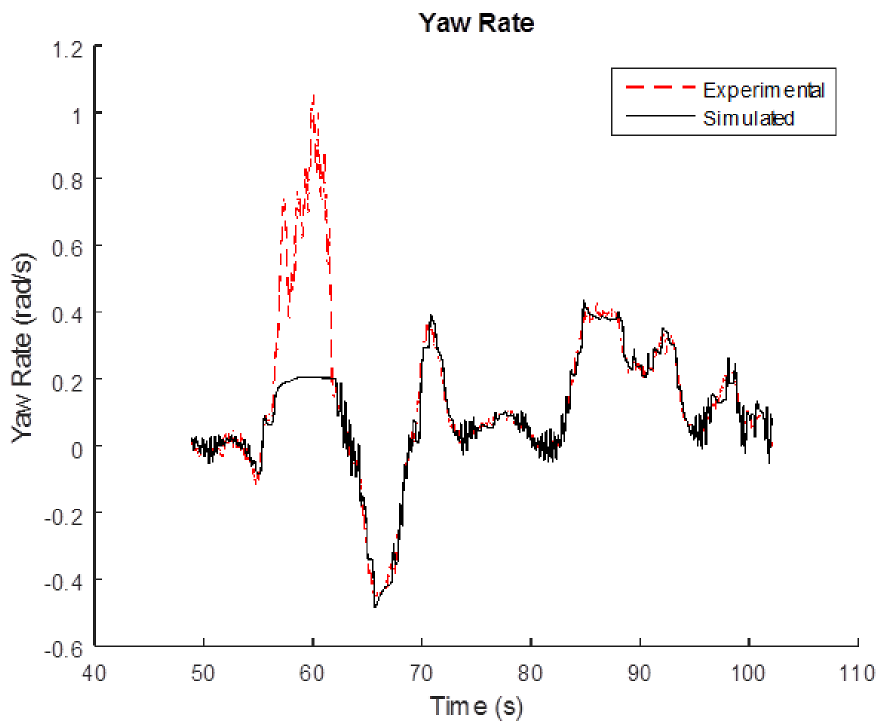


Below are plots that are essentially the starting point for an estimation system. Data was collected for a vehicle doing some random maneuvers, and the steer angle and velocity data was then input into a simulation model to compare some states like slip angle and yaw rate and verify the simulation model. In the plots below it is evident that the simulation tracks with the experimental data quite well.




Rear Slip Angle
Experimental
Simulated
Rear Slip (rad)
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
40
50
60
70
80
90
100
110
Time (s)


Body Slip Angle Beta
Experimental
Simulated
Body Slip (rad)
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
40
50
60
70
80
90
100
110
Time (s)



Yaw Rate
Experimental
Simulated
Yaw Rate (rad/s)
Time (s)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
40
50
60
70
80
90
100
110

References

1. Brudnak, Mark, Patrick Nunez, and Alexander Reid. *Real-time, Distributed, Unmanned Ground Vehicle Dynamics and Mobility Simulation*. Technical rept. no. 2002-01-1178. N.p.: SAE, 2002. Print. SAE Technical Paper Series.

2. Daily, Robert, and William Travis. *Cascaded observers to improve lateral vehicle state and tyre parameter estimates*. Ed. David M. Bevly. N.p.: n.p., n.d. Print.

3. Dattathreya, Macam, and Harpreet Singh. "A Novel Approach for Combat Vehicle Mobility Definition and Assessment." *SAE World Congress* (2012): n. pag. Print.

4. Forkenbrock, Garrick J., comp. *Public Workshop on Dynamic Rollover and Handling Test Techniques*. 3 Dec. 2002, Vehicle Research and Test Center. N.p.: n.p., n.d. Print.

5. Gillespie, Thomas D. *Fundamentals of Vehicle Dynamics*. Warrendale: SAE, 1992. Print.

6. Gray, Jeremy Patrick. "Unmanned Ground Vehicle Terrain/Road Mobility Foundation and Its Algorithmic Formalization for Wheel Power Management to Improve Leader and Follower Capabilities." Diss. The University of Alabama at Birmingham, 2015. Print.

7. Hegazy, Shawky, and Corina Sandu. "Experimental investigation of vehicle mobility using a novel wheel mobility number." *Journal of Terramechanics* 50 (2013): 303-10. Print.

8. Hutangkabodee, Suksun, et al. "Soil Parameter Identification for Wheel-terrain Interaction Dynamics and Traversability Prediction." *International Journal of Automation and Computing* 3 (2006): 244-51. Print.

9. Joo, Sang Hyun, et al. "Real time traversability analysis to enhance rough terrain navigationo for a 6 x 6 autonomous vehicle." *Journal of Mechanical Science and Technology* 27.4 (2013): 1125-34. Print.

10. Senatore, C., and C. Sandu. "Off-road tire modeling and the multi-pass effect for vehicle dynamics simulation." *Journal of Terramechanics* 48 (2011): 265-76. Print.

11. - -. "Torque distribution influence on tractive efficiency and mobility of off-road wheeled vehicles." *Journal of Terramechanics* 48 (2011): 372-83. Print.

12. Treaty on Conventional Armed Forces in Europe, Vienna, 19 November 1990, NATO Summit, available from http://www.osce.org/library/14087?download=true

13. US Army Corps of Engineers: ERDC/GSL. *Standard for Ground Vehicle Mobility*. By E. Alex Baylot, Jr. et al. Technical rept. no. TR-05-6. N.p.: n.p., 2005. Print.

14. Wong, J.Y. *Computer-Aided Methods for Performance and Design Evaluation of Off-Road Vehicles from the Traction Perspective*. Technical rept. no. 2011-01-0266. N.p.: SAE, 2011. Print.

15. Zhang, Yuan. *Drive Point Mobility, Transmissibility and Beyond*. Technical rept. no. 2011-01-0502. N.p.: SAE, 2011. Print.